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HOW UNIVERSAL IS HUBBLE'S LAW?

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1. INTRODUCTION

In 1929 Hubble [1] published his profound result that the spectra of extragalactic nebulae show 'redshifts' in their spectra, with the redshifts increasing as the nebulae get fainter and fainter in the sample. In a typical case a well known absorption line appeared with wavelength $\lambda_0(1+z)$ instead of its laboratory wavelength λ_0, thus implying a redshift z. Taking faintness to be indicative of distance, Hubble's findings implied a relation of the following kind:

$$z = \frac{H}{c}D. \tag{1}$$

Here c = speed of light, D = distance of nebula and H a universal constant now known as Hubble's constant. In terms of apparent magnitude, the above relation becomes:

$$m = 5 \log z + \text{constant}. \tag{2}$$

Hubble's observations have since been extended to distances several hundred times greater and there is a general agreement that a linear law of the above kind holds for 'standard candle' galaxies. These are usually the brightest members of their clusters. Allan Sandage, who has done pioneering work in this field found that such galaxies have almost the same luminosity. Theoretically (2) is an approximation for a more general redshift-distance law,

$$z = \frac{H}{c}f(D) \tag{3}$$

where $f(D) \approx D$ for $D \ll c/H$. This law is known as Hubble's law and it forms the basis of standard cosmology with the basic framework of an expanding universe. We will refer to the expanding universe hypothesis as the cosmological hypothesis (CH). It implies that *objects at the same distance have the same redshift.*

Yet, how 'universal' really is Hubble's law? Does it apply uniformly to all extragalactic objects? Or are there some exceptions? We will examine a number of anomalous cases where the law appears to break down. We begin with Hubble's original plot itself!

2. A NONLINEAR HUBBLE RELATION

Figure 1 shows a figure reproduced from an analysis of Hubble's original velocity distance relation by Hewitt and Burbidge [2]. The upper plot is according to modern measurements of redshifts and magnitudes while the lower one is that of Hubble. The reader may draw his own conclusion as to whether the revised plot could have suggested a linear relation to Hubble!

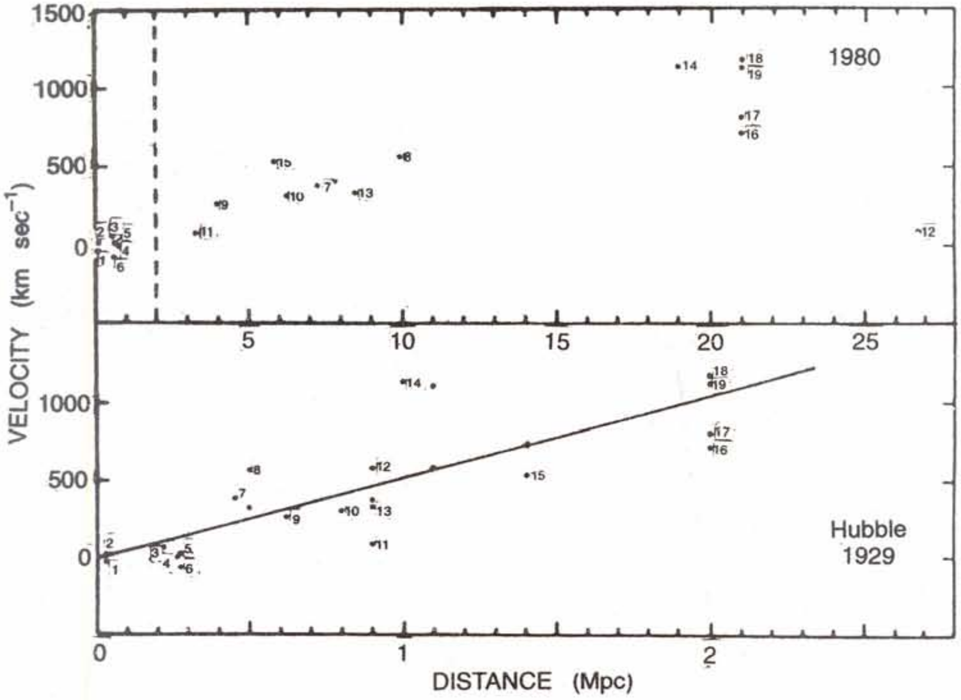

Figure 1: Hubble's original plot is shown below the modern plot prepared in 1980 by Hewitt and Burbidge.

Others have raised doubts concerning the linearity of the velocity–distance relation for bright galaxies. For example, Hawkins [3] has claimed that the velocity–distance relation is in fact quadratic. He points out that the 430 galaxies brighter than 14^m that constitute 91% of the sample of Humason *et al.* [4] show a redshift-magnitude relation of the form

$$m = 2.26 \log z + \text{constant}, \tag{4}$$

instead of the Hubble slope of 5. A quadratic law would in fact predict a slope $dm/d(\log z) = 2.5$ and Hawkins claims that the 'best fit' slope of 2.26 is closer to this value than to 5 required by the linear Hubble law. According to Hawkins there are systematic observational biases that can change the 'true' quadratic law to a 'false' linear law.

Segal [5] has given a detailed statistical analysis of the m–z data for bright galaxies in the range $[500 < cz < 2500 \text{ km s}^{-1}, m < 12.5^m]$ from the work of

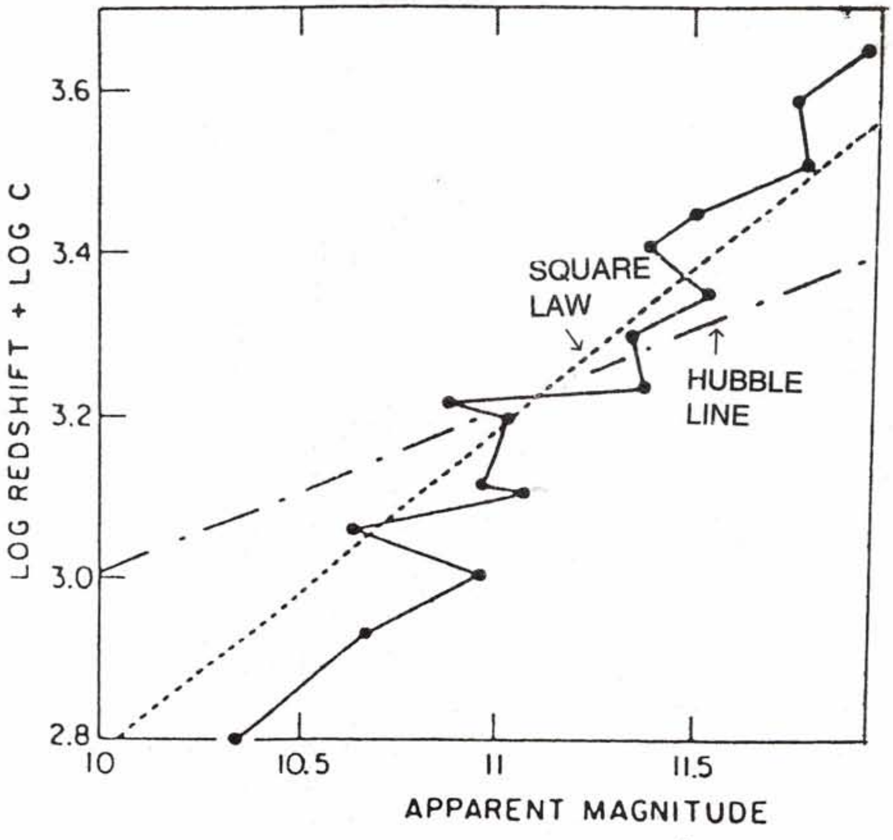

Figure 2: The m–z plot of Segal shows a better aggrement with $z \propto D^2$ law than with the linear law.

Sandage and Visvanathan [6]. Figure 2 shows his m–z plot with the lines for linear and quadratic laws superposed on the data points. Again, it appears that the quadratic law gives a better fit than the linear law.

These claims have, however, been refuted by Sandage and Tammann [7] and Soneira [8] who show that the linear relation gives a better fit. They attribute the apparent quadratic law to the Malmquist bias. The Sandage–Tammann plot based on the sizes of HII regions in a sample of nearby SC galaxies is given in Figure 3.

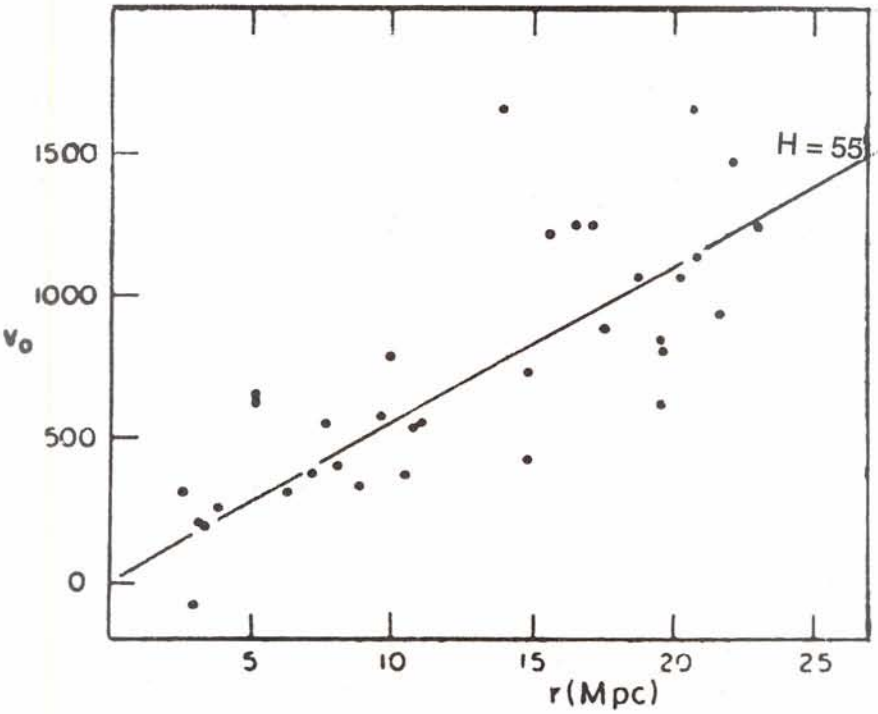

Figure 3: Sandage and Tammann have argued that for spiral SC galaxies the above plot fits the Hubble law (shown by the straight line).

(In the Malmquist bias, as we examine progressively more distant galaxies we tend to pick a larger and larger fraction of the brighter members of the sample.)

3. PERIODICITIES IN THE REDSHIFT DISTRIBUTION

In a homogeneous and isotropic universe we expect the redshift distribution of extragalactic objects to approximate to a continuous and aperiodic distribution. In the Friedman universe, the coordinate volume of the shell sandwiched between radial coordinates r and $r + dr$ is given by

$$dV \sim \frac{r^2 dr}{\sqrt{1 - kr^2}}, \tag{5}$$

since there is a unique relationship between r and z, this translates to

$$dV \sim \frac{[q_0 z + (q_0 - 1)(\sqrt{1 + 2q_0 z} - 1)]^2 z}{(1 + z)^3 \sqrt{1 + 2q_0 z}}. \tag{6}$$

Unless there is an epoch dependent evolution, the observed redshift distribution of discrete sources will simulate this continuous and aperiodic distribution. If a survey is magnitude/flux density limited then the above distribution will be truncated appropriately by folding in the luminosity function. Again, this further input will not change the expected continuous nature of the observed redshift distribution. Various observers, however, have reported results that suggest discreteness or periodicity in the redshift distribution, contrary to the above expectation. We group the data under two headings: (i) nearby galaxies and (ii) quasi-stellar objects.

3.1 NEARBY GALAXIES

Studies of non-dynamical correlations between redshift, magnitude, and morphology in clusters of galaxies led Tifft in the mid-1970s to indications of periodicity within m–z band [9–10]. The characteristic redshift interval came out to be ~ 72 km s^{-1} (for cz). However, to establish peridocity at this level it was essential to reduce the error bars on the cz-measurements below the ~ 25 km s^{-1} limit then existing.

By 1982 high quality measurements with 21 cm wavelength became available for galaxies in small groups with the accuracy $\Delta(cz) < 9$ km s^{-1}. Using these data Tifft confirmed that the earlier effect still held quite unambiguously [11].

How the data have improved in quality over the years is shown in Figures 4 and 5. In Figure 4 we see Tifft's analysis of double galaxy data showing the distribution of Δcz in double galaxies, ranging up to 250 km s^{-1} with $\sigma < 50$ km s^{-1}. The numbers are counted in cells 36 km s^{-1} wide, centred at values of $N \times 36.07$ km s^{-1} for $N = 0$–6. The normal distribution curve of same area and dispersion is shown by the dotted line in the upper histogram.

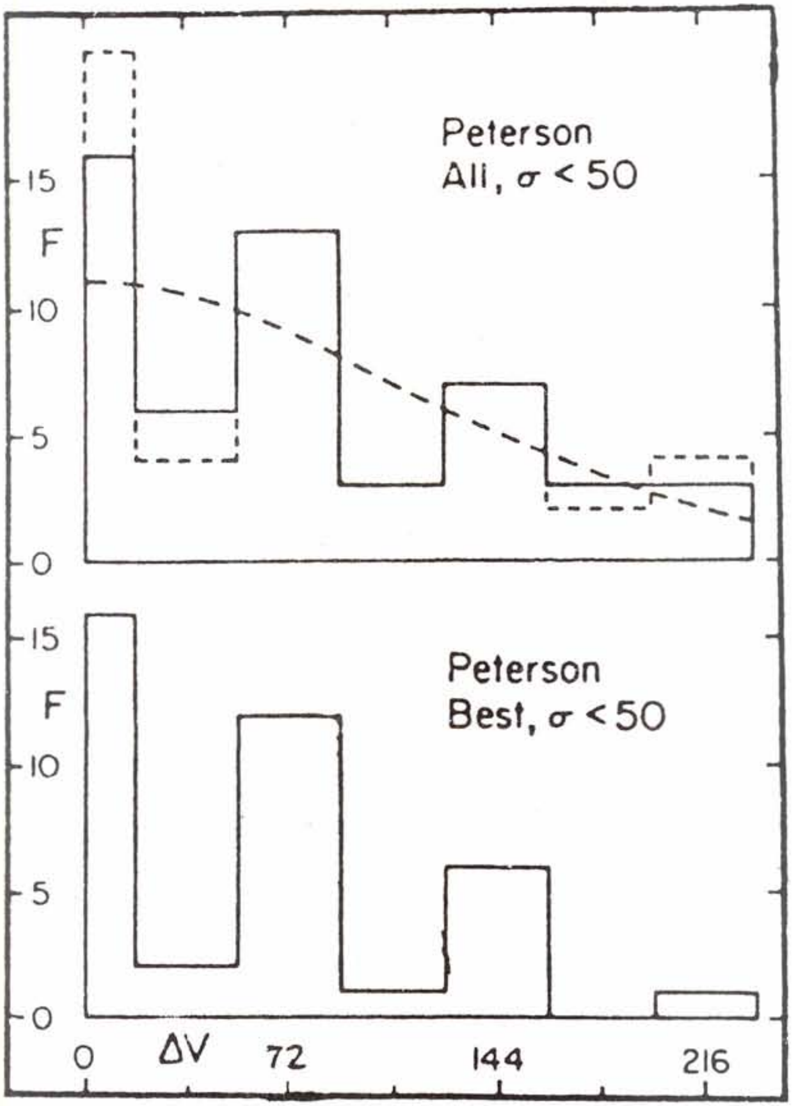

Figure 4: The histogram of velocity differentials prepared by Tifft in 1979 from data on double galaxies. The peaks at multiples of 72 km s^{-1} are clearly seen.

In Figure 5 we see the result obtained by Arp and Sulentic [12] for 260 galaxies from more than 80 groups. Of these 160 galaxies are taken from the Rood

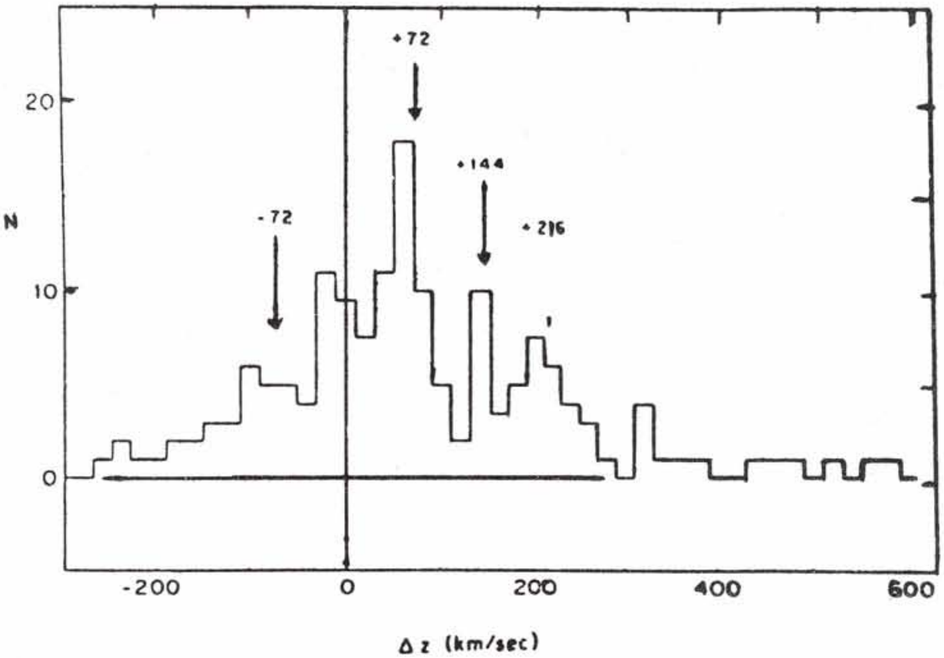

Figure 5: The histogram of velocity differentials between large galaxies and their statellites prepared by Arp and Sulentic in 1985. The observations use 21 cm measurements and are much more accurate than in Figure 4. The peaks are again clearly visible.

catalogue where the accuracy of $\Delta(cz)$ measurements (with the 21 cm line) is as good as 8 km s^{-1}. The remaining 100 are as accurate as $\Delta(cz) < 4$ km s^{-1}. The typical system has a large galaxy with a satellite companion usually with excess redshift $\Delta(cz) > 0$. With such improved accuracy the peaks stand out at multiples of 72 km s^{-1}.

It is worth remarking that the Tifft effect has survived critical examination by statistitians. For example, Napier *et al.* [13] have subjected these data to power spectrum analysis based on the classical theory of random walks. They find the effect to be real at a highly significant level with the chance probability $< 10^{-4}$.

Apart from the fact that the effect has survived improved data and independent statistical checks, its most disturbing aspect for conventional physics is that there appears to be no explanation for it within the known theoretical framework. Taken at face value it implies that if the CH is valid the space has some discrete structure on the scale of $\sim 0.72 h_0^{-1}$ Mpc!

3.2 QUASI-STELLAR OBJECTS

Another line of evidence at the higher redshifts of the quasi-stellar objects or QSOs has been reported from time to time. Burbidge [14] suggested that the peaks in the observed distribution of redshifts of QSOs continued to persist in spite of addition of new redshifts and that they indicated a periodicity. The issue has been discussed many times before. The earlier work of Burbidge and O'Dell [15] involving 346 redshifts had concluded that although more sources were seen with $z = 1.95$ and 0.061 than expected by chance, the statistical significance of the result was not certain. They did find, however, that there was an underlying periodicity of $\Delta z = 0.031 (\sim \frac{1}{2} \times 0.061)$ in the redshift distribution that was significant.

Subsequently, Karlsson [16] made a power spectrum analysis of QSO redshifts to conclude that the peaks in the redshift distribution were significant and occurred with a period

$$\Delta \log (1 + z) = 0.089. \tag{7}$$

The peaks occur at $z = 0.30, 0.60, 0.96, 1.41, 1.96$. More recently Duari *et al.* [17] have reconfirmed the linear Burbidge periodicity for a sample of > 2000 quasars. The mystery therefore remains despite enlargement of samples. Nor can we find any connection between this and the Tifft-type periodicity.

4. GALAXY-GALAXY ASSOCIATIONS

Although we find a tight Hubble relation of first ranked galaxies in clusters, there are a number of apparently discordant cases involving galaxies. Recall that the CH requires two galaxies at the same distance to have the same redshift. Astronomers do not have very reliable measures of distances: hence if two galaxies are seen very close to each other on the sky we cannot a-priori tell if they are physical neighbours or their directions happen to be nearly the same. Additional evidence is therefore needed. We may broadly classify the evidence into two categories depending on whether there is a physical connection between two galaxies with different redshifts. In what follows we will consider the redshift differences between two neighbouring galaxies significant if they cannot be accounted for by a random relative motion of up to $\sim 10^3$ km s^{-1} between the two i.e., by a Doppler effect.

4.1 UNCONNECTED NEIGHBOURS

Figures 6–8 show photographs of unusual groups of galaxies. For a detailed discussion of their features see Arp [18]. The first photograph shows the barred galaxy NGC 3718 near the chain of smaller galaxies VV 150 from the atlas of interacting galaxies compiled by Vorontsov–Velyaminov. The chain appears to have tidal interaction with NGC 3718, disrupting it in the process. However, the chain has excess redshift $cz \simeq 7 \times 10^3$ km s^{-1} with respect to the Galaxy.

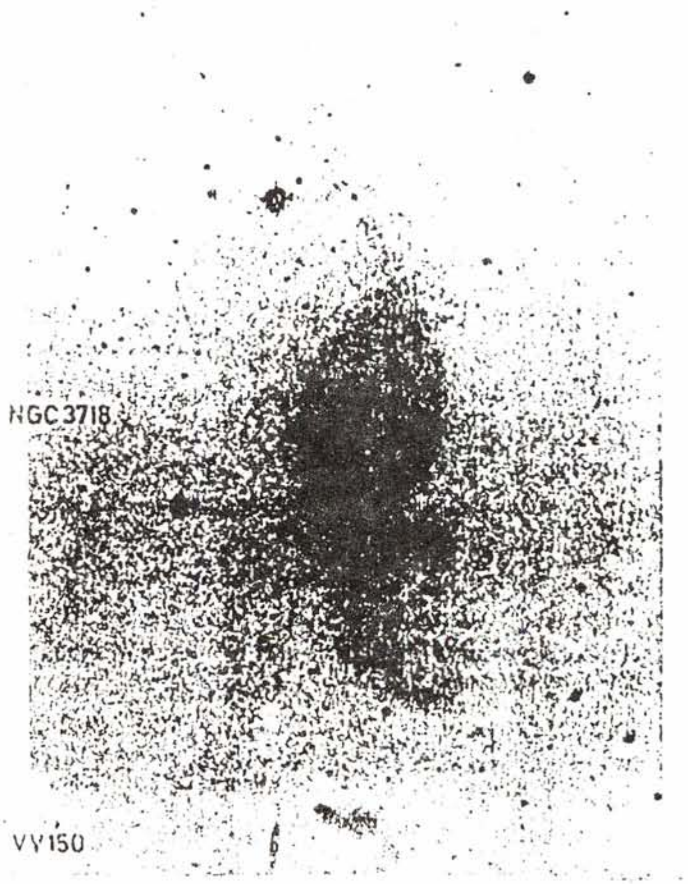

Figure 6: The chain of galaxies VV 150 with the barred galaxy NGC 3718 shown nearby. The chain has an excess redshift relative to NGC 3718. *Photo by courtesy of Chip Arp.*

In the more famous chain VV 172 of the five galaxies seen in Figure 7 four have similar redshifts $cz = 16070$ km s^{-1}, 15820 km s^{-1}, 15690 km s^{-1} and

15840 km s^{-1} as expected for neighbours in a group. However the redshift of the second galaxy from top is $cz = 36880$ km s^{-1}. According to Hubble's law, this should not be part of the chain but a more distant object and as such it should have comparatively more reddish colour. Instead, it is abnormally blue in colour! Also if it were really as far away as suggested by the CH, then it would have to be abnormally large! More spectroscopic work needs to be done on VV 172 to settle the issue one way or the other.

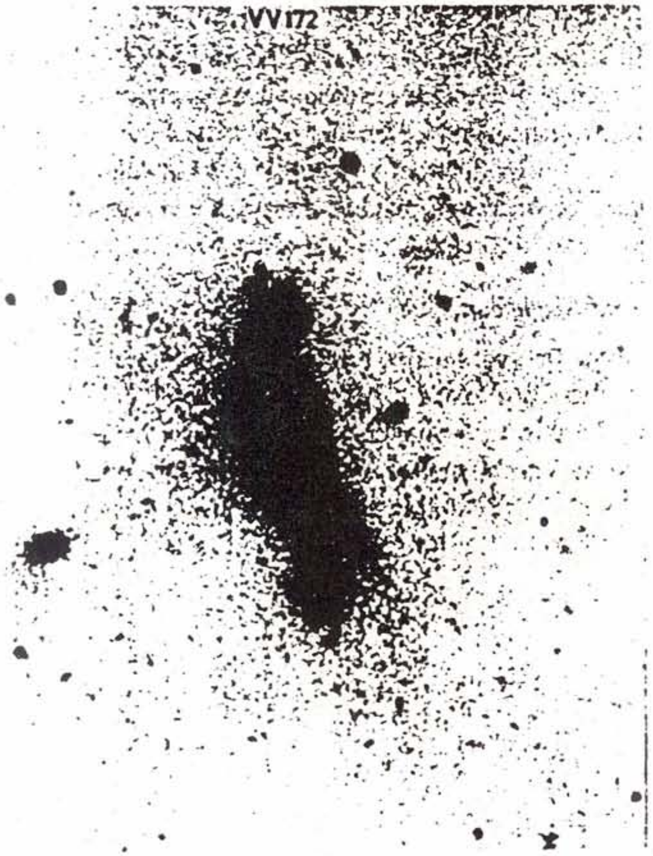

Figure 7: The chain VV 172 with the second member from top having an excess redshift with respect to the other four. *Photo by courtesy of Chip Arp.*

The most famous example of this kind, known as Stephan's quintet was first discovered by M.E. Stephan in 1877 and is shown in Figure 8. Its peculiarity became noticeable when Burbidge and Burbidge [19] studied it spectroscopically.

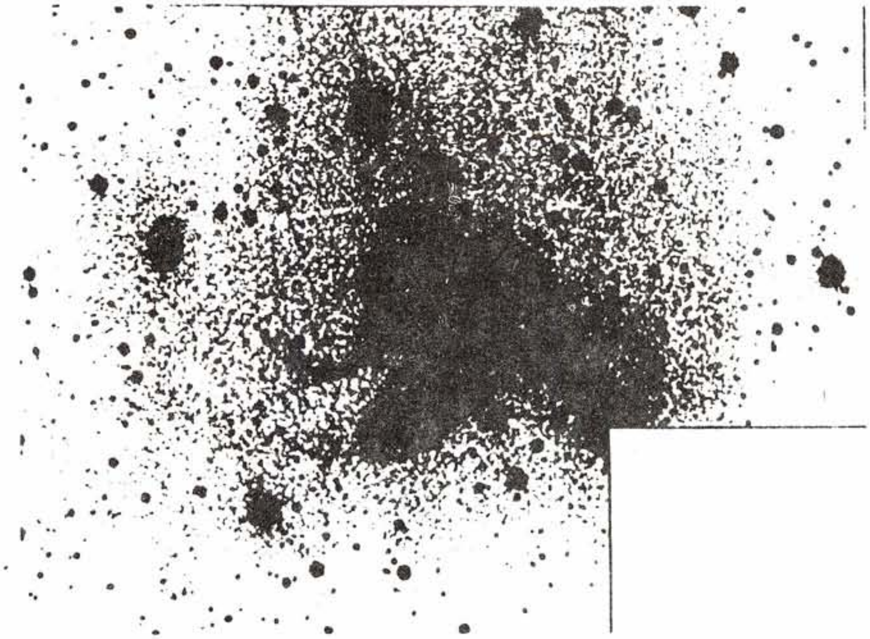

Figure 8: Stephan's quintet. *Photo by courtesy of Chip Arp.*

They found that the largest member of the quintet (the one in bottom left-hand corner) is the galaxy NGC 7320 with a redshift cz of only 800 km s^{-1} whereas the cz-values of the other four members are 5700, 6700, 6700 and 6700 km s^{-1}. The galaxies all appear to be interacting considering their unusual shapes. As CH would have it, NGC 7320 is a foreground object with no physical proximity to the others. Arp [18[18]] has argued strongly that this interpretation is incorrect. According to Arp, NGC 7320 is a perfectly normal dwarf galaxy while the other four have irregular shapes indicating that their excess redshifts (with respect to NGC 7320) are noncosmological. Indeed, Arp finds that the Stephan quintet along with a few other redshift companions are all satellite members of NGC 7331, a large Sb galaxy with redshift nearly the same as that of NGC 7320. As supporting evidence he points to radio-emitting material connecting NGC 7331 to the quintet. Again, this point of view is hotly debated and no definite conclusion is yet possible.

Typical examples of this kind are shown in Figures 9–11. Again, for details of

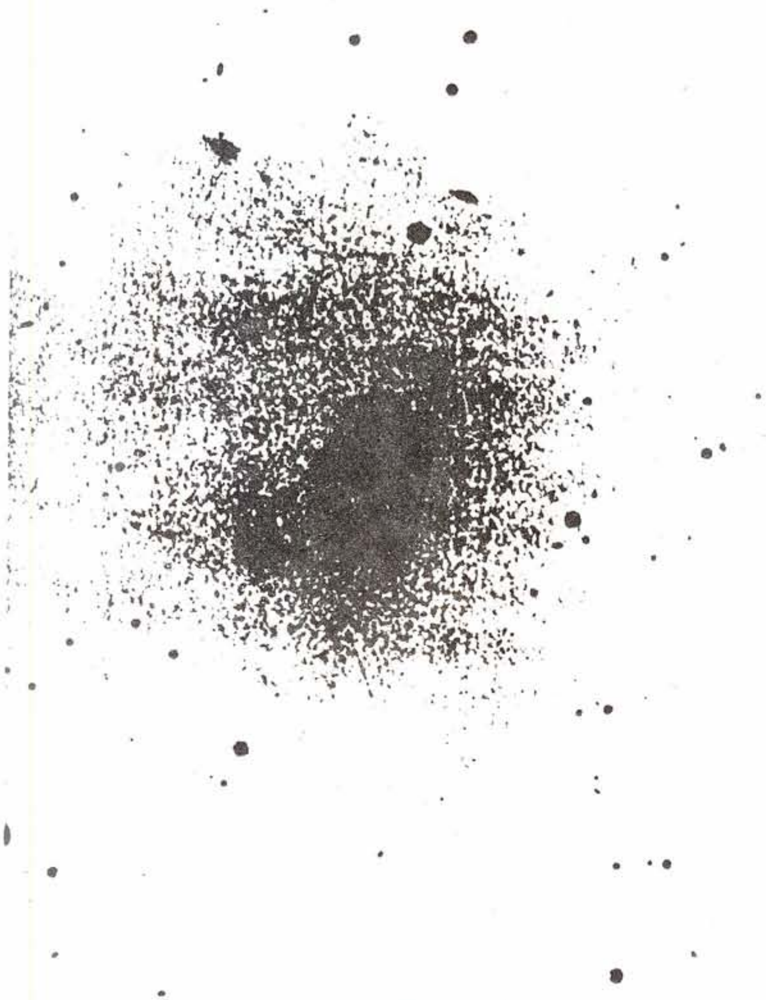

Figure 9: The large galaxy NGC 7602 ($cz = 8700$ km s^{-1}) is apparently connected to a companion ($cz = 16900$ km s^{-1}). *Photo by courtesy of Chip Arp.*

these systems see Arp [18]. The standard pattern running through these cases is the following. The photographic evidence shows some filamentary structure joining two galaxies, one of them a large NGC galaxy and the other a small, compact galaxy. The filament starts at the former and ends at the latter, suggesting that the compact member was somehow ejected from the bigger object.

4.2 CONNECTED NEIGHBOURS

Filamentary structures linking two galaxies are not uncommon and it is customary to see the pair of galaxies as interacting tidally. Figure 12 is a well-known example of this kind, known as the 'toadstool'. However, what distinguishes the cases found by Arp from a case like the toadstool is that in the latter there is no discrepancy regarding redshifts. Not so in Figures 9–11! For example, the *cz*-values of the main and the companion galaxies in Figure 9 are

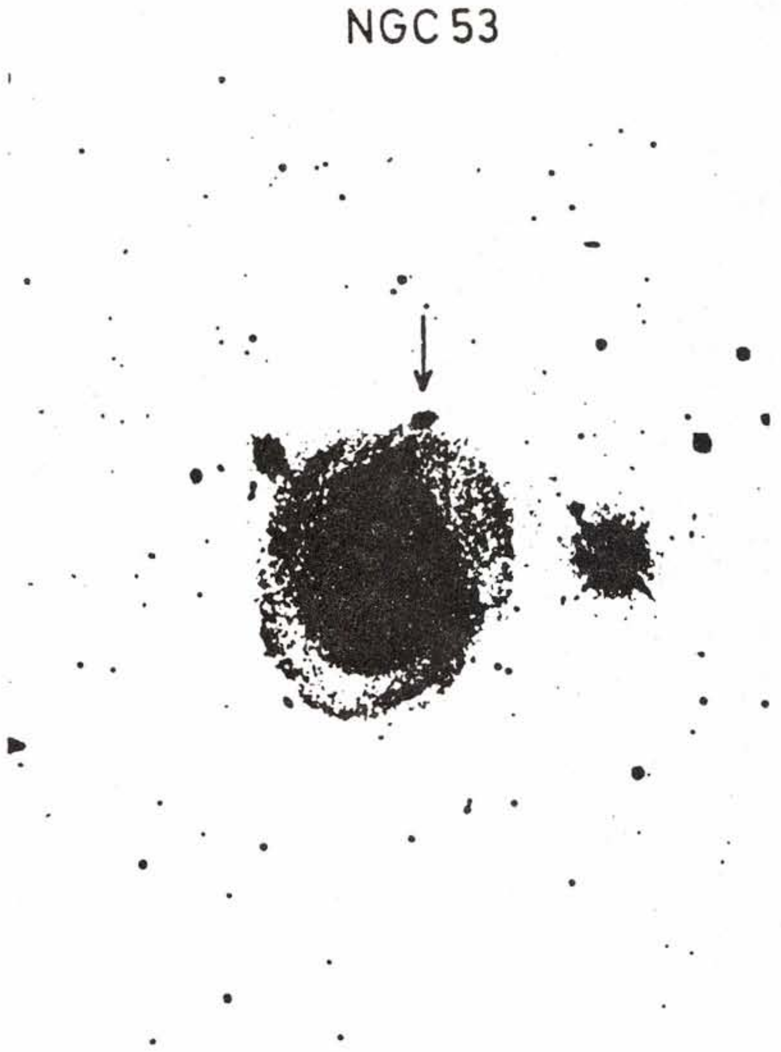

Figure 10: The large galaxy NGC 53 ($cz = 4160$ km s^{-1}) has a filament linking it to a companion ($cz = 37000$ km s^{-1}). *Photo by courtesy of Chip Arp.*

8700 km s^{-1} and 16900 km s^{-1}. Normally we should suspect velocity differences exceeding 1000 km s^{-1}.

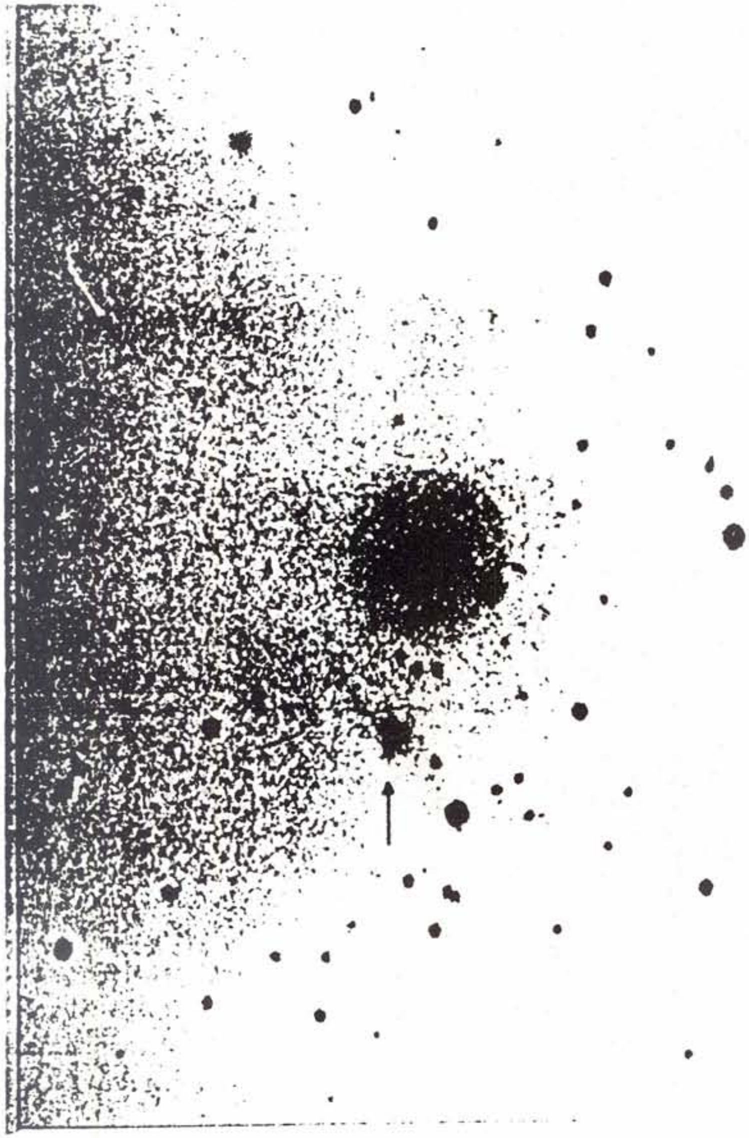

Figure 11: Another combination of main galaxy ($cz = 10400$ km s^{-1}) linked to a companion ($cz = 46900$ km s^{-1}) in the catalogue of Southern Peculiar Galaxies and Associations (Catalogue number AM 2054–2210). *Photo by courtesy of Chip Arp.*

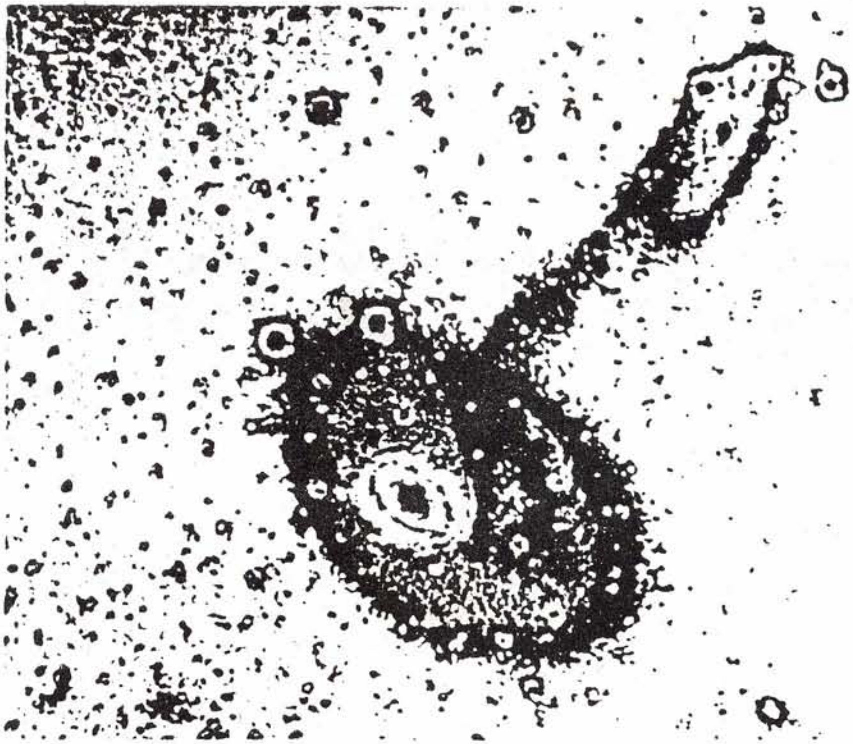

Figure 12: The 'Toadstool' showing interacting galaxies.

Are we seeing in such cases a breakdown of the CH? If the differences in the *cz* motions as large as in the above examples are accepted as normal, then one should not be seeing the Hubble expansion effect for these nearby galaxies at all. So the only way to sustain the CH is to argue either that the filamentary connection is not real but an artefact or that the compact galaxy is really much farther away and happens by chance to have been projected at the end of the filament.

The former alternative was indeed advocated for the system shown in Figure 13 wherein a filament linking NGC 4319 with a QSO like object Markarian 205 was found by Arp in 1971. The redshifts of these objects are quite different and hence it was argued that the filament is a photographic artefact. However, the system was subjected to imaging techniques of electronics by Sulentic in 1984 who established the reality of the filament [20] (see Figure 14).

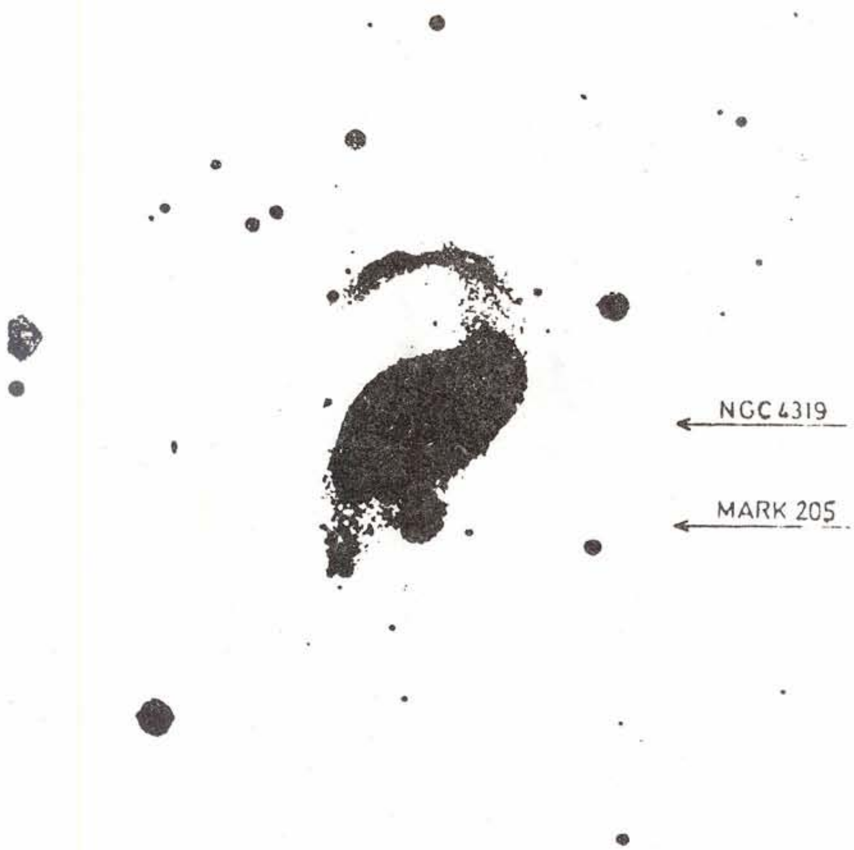

Figure 13: The connnection between NGC 4319 and M 205 found by Arp.

We next present evidence suggesting physical association between bright, low redshift galaxies and QSOs of substantially higher redshifts. In that sense the case of NGC 4319 + Markarian 205 might belong to the next section.

5. ASSOCIATIONS BETWEEN QSOs AND BRIGHT GALAXIES

The first systematic attempt to look for close pairs of QSOs and galaxies, *irrespective of redshifts*, was made by Burbidge *et al.* [21]. These authors looked for distributions rather than isolated instances of QSOs and galaxies; in this case they compared the radio loud QSOs from the 3CR catalogue with the galaxies in the Shapley-Ames catalogue. They found a significant statistical effect which was later confirmed also by Kippenhahn and de Vries [22]. However, a similar analysis

Figure 14: Sulentic's electronic image processing shows the connection between NGC 4319 and M 205.

using the QSOs from the Parkes radio catalogue and the galaxies in the Zwicky catalogue yielded a far less pronounced effect. Hazard and Sanitt also discounted the effect after a comparison of other QSO samples with the Shapley-Ames galaxies. As Burbidge *et al.* [23] themselves point out, comparison of samples containing farther galaxies or/and fainter QSOs increases the population densities and hence the probability of a chance association. The effect is more apparent for bright galaxies and QSOs.

Amongst other attempts to look for associations between population of QSOs and galaxies may be mentioned the work of Seldner and Peebles [24] who found a statistically significant evidence for association. Their QSO population numbered 382 with $|b| > 40°$, $\delta > -23°$ and the galaxies came from the Lick counts

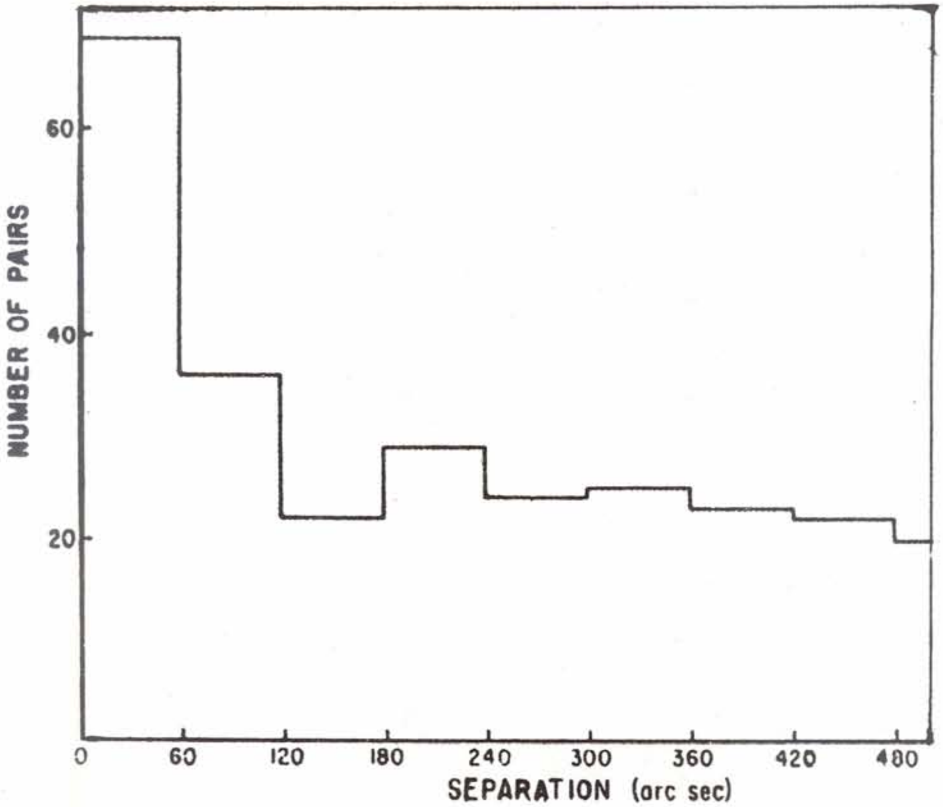

Figure 15: The histogram of angular separation between quasars and bright galaxies shows significant correlation at small angular scales. If quasar distribution were unrelated to galaxy distribution we would have seen more quasar-galaxy pairs at progressively larger angular separations.

going down to 19^m. These authors found on the average 1.45 ± 0.39 more galaxies within 15′ of a QSO than expected under a random arrangement. The effect does not seem related to the redshifts of the QSOs in the sample. More recently DasGupta *et al.* [25] have found considerable evidence in favour of QSOs and bright galaxies. Figure 15 illustrates one of their statistical studies.

Arp and his coworkers have produced several isolated examples of dense concentrations of QSOs around companion galaxies near the NGC galaxies. For a review of such cases see Arp [18]. A striking example is shown in Figure 16 where we see a dense concentration of 9 QSOs discovered by Arp and Hazard. There are four galaxies in the field. Is the concentration significant?

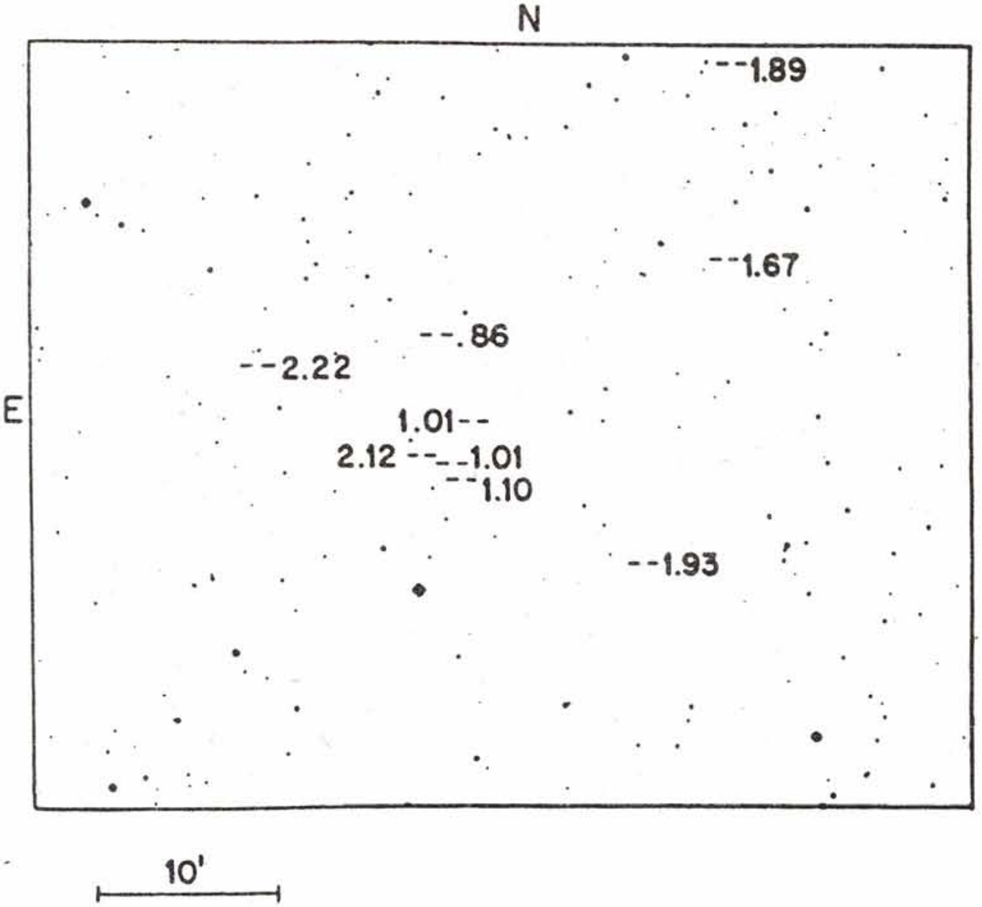

Figure 16: The concentration of QSOs with redshifts marked in the vicinity of the region of right ascension $11^h46^m14^s$ and declination 11°11′42″ found by Arp and Hazard.

In the early 1970s, Burbidge *et al.*[21] reported a peculiar empirical relation between the angular separation θ between the QSO–galaxy pair and the redshift z of the galaxy. The relation obtained for five pairs with the QSOs taken from the 3CR catalogue is shown in Figure 17. The five points lie very close to the line

$$\log \theta + \log z = \text{constant}. \tag{8}$$

Why should such a relation emerge, if the QSOs (according to the CH) happen to be projected by chance near the galaxies?

If the two members of the pair are at the same distance (as indicated by the galaxy redshift) then the above result implies that the linear separation between

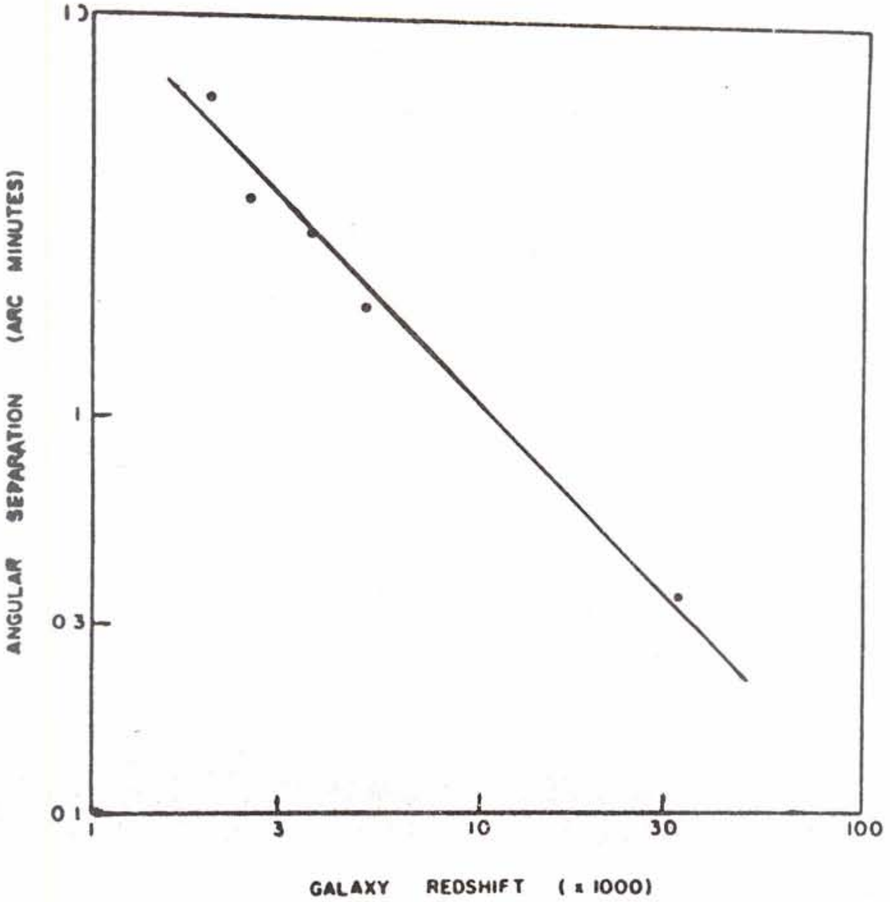

Figure 17: The $\theta \propto z^{-1}$ found by Burbidge *et al.* is difficult to understand on the basis of the CH.

the two, projected perpendicular to the line of sight, is constant. It may be that in a local theory, the linear separation stays within narrow limits, in which case, due to projection effects we expect to see a scatter around the line. This has indeed been borne out by the work of DasGupta *et al.* [25].

6. ALIGNMENTS AND REDSHIFT BUNCHING

In astronomy we often interpret alignments of objects on the sky in terms of some physical mechanism of ejection. The most striking example of this practice is found in the double lobed radio sources whose lobe centres are very often seen as aligned across a central galaxy. The usual interpretation of these objects is in terms of a central black hole ejecting plasma in a highly collimated fashion in opposite directions. The lobes arise when the plasma impinges on the intergalactic medium and radiates.

Highly suggestive alignments have been found between QSOs in relation to a central bright galaxy and in some cases between QSOs without reference to a galaxy. Figures 18–19 illustrate QSO-galaxy alignments while Figure 20 shows a remarkable double alignment of two triplets found on the same photographic plate by Arp and Hazard [26].

In Figures 18–19 the separations between the QSOs and the galaxy are of the order of several arc minutes ranging upto a degree or so. Notice also that in many

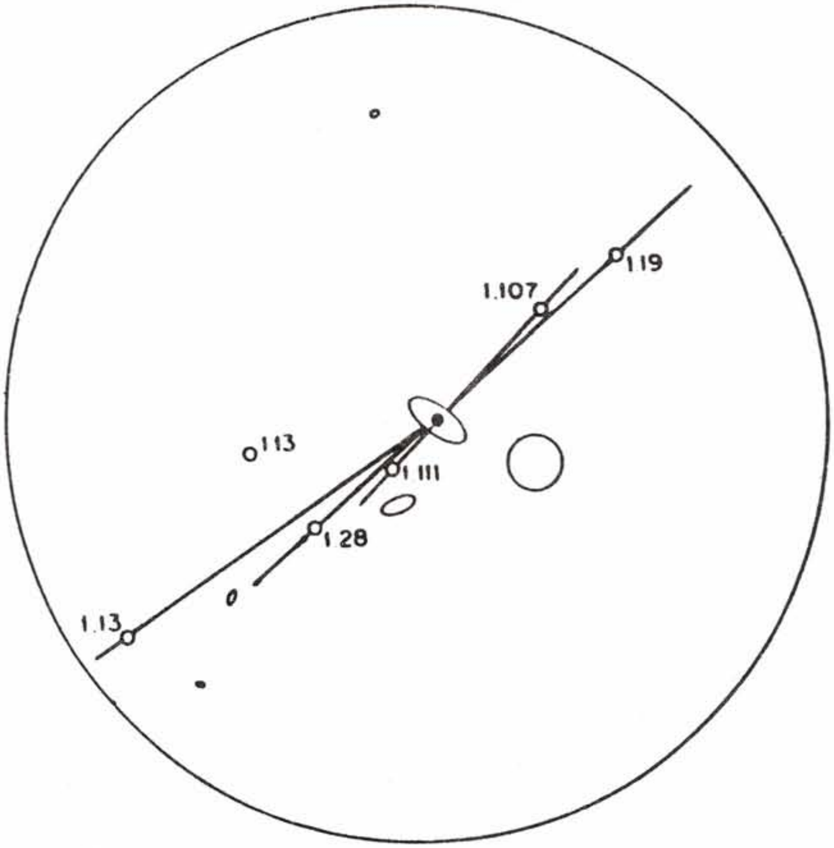

Figure 18: **The alignment of quasars with bunched redshifts (marked in the figure) across the galaxy NGC 3384.** ***Source*: *Ref.* [18].**

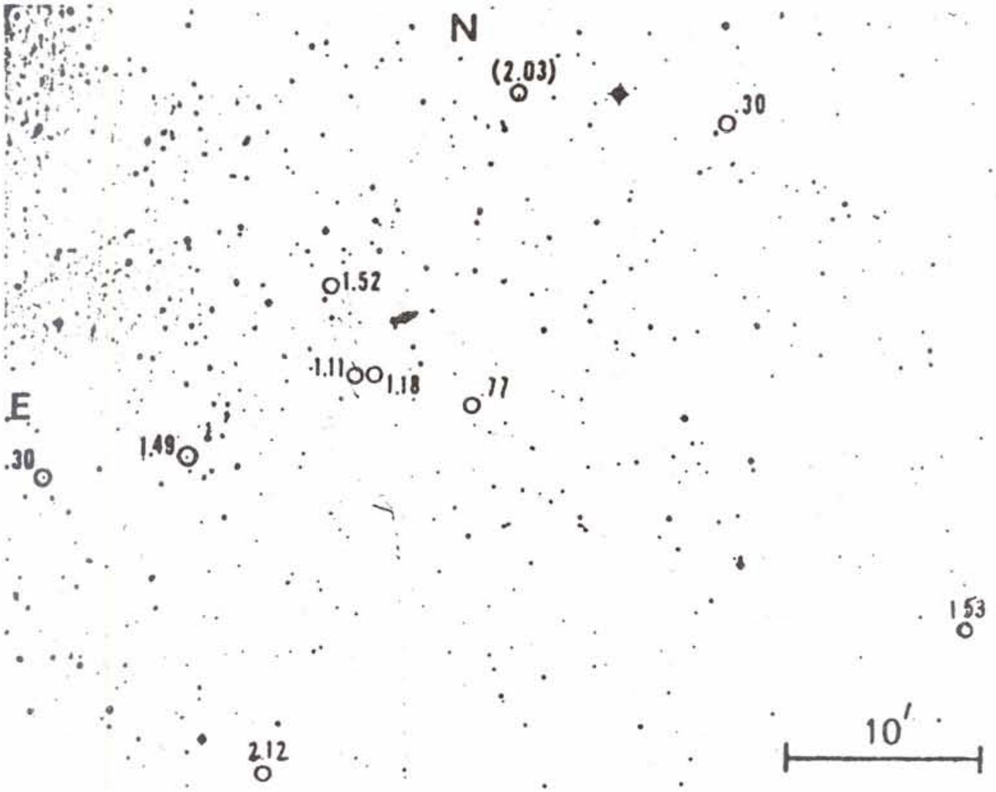

Figure 19: Ten quasars surrounding a companion galaxy to NGC 2639. The alignments and redshift bunching are also seen. *Source*: *Ref.* [18].

cases the QSO redshifts are bunched around values in relatively small intervals. Not all of these data can be put down to selection effects. Are these alignments across the galaxy and the redshift values entirely coincidental? It is fair to say that although *a posteriori* probabilities for these configurations have been computed and shown to be very small, they are also subject to considerable debate.

7. SUMMARY

We have discussed the discordant evidence in its various aspects. Technically, to disprove a well established hypothesis one discordant piece of evidence is sufficient; provided the discordant nature of the evidence is clearly established and generally accepted after a critical examination.

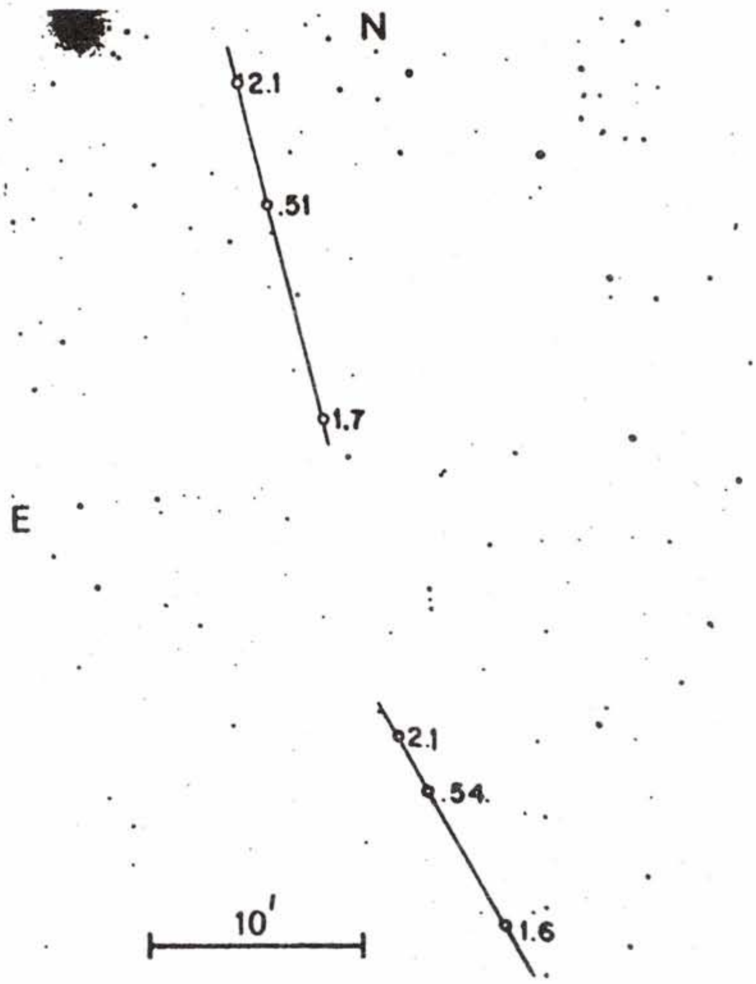

Figure 20: Two aligned triplets with redshifts (respectively) very similar found by Arp and Hazard.

If Hubble's law does not hold, then the redshift z of any extragalactic object will have a noncosmological component, z_{nc}. Typically we may write

$$1 + z = (1 + z_c)(1 + z_{nc}). \tag{9}$$

Of this z_c obeys the Hubble law but z_{nc} does not. The CH can be critically tested by looking for z_{nc}. If discrepant cases with $z_{nc} \neq 0$ are objectively looked at we may be able to decide whether Hubble's law is universally valid. Rejection of any discordant evidence is of course justified provided it has been subjected to proper scrutiny and debate.

This procedure has not been followed with the different cases discussed here. The discussion in many cases has actually been cursory and in some cases the results are simply ignored. The general attitude is: Ignore a discordant case because it is inconsistent with Hubble's law. Surely, with this attitude the Hubble law itself cannot be critically examined!

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